INNOVATIVE TECHNOLOGY

Summary Report

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Vadose Zone Characterization System

Tanks Focus Area

Prepared for

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INNOVATIVE TECHNOLOGY
Summary Report

Vadose Zone Characterization System

OST/TMS ID 2118

Tanks Focus Area

Demonstrated at
Hanford Site
Richland, Washington

INNOVATIVE TECHNOLOGY
Summary Report

Purpose of this document

Innovative Technology Summary Reports are designed to provide potential users with the information they need to quickly determine whether a technology would apply to a particular environmental management problem. They are also designed for readers who may recommend that a technology be considered by prospective users.

Each report describes a technology, system, or process that has been developed and tested with funding from DOE's Office of Science and Technology (OST). A report presents the full range of problems that a technology, system, or process will address and its advantages to the DOE cleanup in terms of system performance, cost, and cleanup effectiveness. Most reports include comparisons to baseline technologies as well as other competing technologies. Information about commercial availability and technology readiness for implementation is also included. Innovative Technology Summary Reports are intended to provide summary information. References for more detailed information are provided in an appendix.

Efforts have been made to provide key data describing the performance, cost, and regulatory acceptance of the technology. If this information was not available at the time of publication, the omission is noted.

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SECTION 1
SUMMARY

Technology Summary

Background
The U.S. Department of Energy (DOE) has employed geophysical methods for characterization of hydrogeologic conditions and/or contaminant distributions at the Hanford Site since the 1940s (Last and Horton 2000). Each of the 177 underground waste tanks is ringed by a number of dry, 100- to 150-ft-deep boreholes used to establish the depth of gamma ray contamination beneath tank farms. The DOE Grand Junction Project Office was tasked in the mid 1990s to perform a baseline characterization of plumes using the boreholes around single-shell tanks (SSTs). Extensive three-dimensional mapping of gamma contamination in the vadose zone beneath SSTs is available through the Grand Junction Project Office Web site at http://www.doegjpo.com/programs/hanf/HTFVZ.html.

The Government Accounting Office (GAO) reported in March 1998 that DOE's understanding of how contaminated waste moves through the vadose zone to the groundwater is inadequate to make key technical decisions on how to clean up the contamination at the Hanford Site (GAO 1998). A June 2000 report by Pacific Northwest National Laboratory (PNNL) stated that additional information is needed about the processes controlling transport beneath Hanford tank farms (Ward and Gee 2000).

Problems

- The ability to obtain additional characterization data on contaminated plumes at new locations beneath tank farms is limited by accessibility within tank farms. Conventional drill rigs most often cannot be located over plumes in tank farms because of surface piping, instrument lines, and utilities.
- Drilling and analysis costs in T and SX tank farms have exceeded $1 million per borehole.
- Drilling may produce contaminated drilling mud.
- The sample analysis may take months to complete.
- Boreholes produce localized measurements unsuitable to characterize an entire plume.
- Additional characterization of entire plumes by use of new boreholes is cost-prohibitive.

Solution
The Vadose Zone Characterization System (VZCS) uses a cone penetrometer (CP) with gamma sensors to characterize gamma contamination in the vadose zone under tank farms. A magnetometer in the CP tip reduces the probability of contacting subsurface utility or instrument lines during use. A truck-mounted VZCS (see Figure 1) can be driven into tank farms and located in any area the size of a parking space. A platform-mounted VZCS (see Figure 2) can be lifted by a crane into locations that have no vehicle access.

Figure 1. Truck-mounted Vadose Zone Characterization System.

Figure 2. Stand-alone cone penetrometer platform used to deploy the Vadose Zone Characterization System.

Because of rapid deployment and lower cost, the VZCS can characterize an entire contamination plume for the same cost as a single borehole installation. Gamma contamination can be characterized to a depth of 150 ft in one day for a fraction of the cost of conventional drilling.

How It Works

The VZCS consists of multifunction probes within a CP that is pushed from a stand-alone or truck-mounted platform into the ground to depths up to 150 ft. Probes inside the tip of the CP measure the vadose zone soil for gamma-emitting contaminants. The multisensor probe (MSP) configuration includes three modules:

- The screening module uses X-ray fluorescence (XRF) and gamma spectroscopy (GS) sensors to detect target radioactive contaminants.
- The tip module has stress sensors that help identify soil stratigraphy, a magnetometer sensor to detect subsurface ferrous structures, and an inclinometer sensor to monitor the CP's vertical alignment during penetration.
- The soil moisture and resistivity (SMR) module enables the measurement of soil moisture content and soil resistivity, both important in determining soil stratigraphy and contaminant migration.

Two other probes were demonstrated: a multipoint soil sampler probe (SSP) to retrieve soil samples in a separate push and a grouting tip to close the CP hole.

Potential Markets

The VZCS is less intrusive than conventional drilling methods. It can be used to collect qualitative and quantitative information at contaminated vadose zone and groundwater sites to depths up to 150 ft. Analytical parameters can be monitored in real time through various sensor probes incorporated in the VZCS.

Advantages over Baseline

The baseline technology for subsurface characterization of radioactive plumes is drilling a borehole and collecting soil samples during drilling, then analyzing the samples in a laboratory. The baseline technology can be supplemented with the VZCS to gain the following advantages:

- rapid deployment in tank farms,
- magnetometer in tip to detect and avoid subsurface lines,
- ability to obtain a subsurface gamma profile at a specific location before drilling an expensive borehole,
- 30–60% cost avoidance realized when using the technology to optimize the location of monitoring boreholes,
- real-time measurement of certain contaminants,
- real-time measurement of moisture in soil,
- no drilling waste, and
- less disturbance of subsurface compared with conventional drilling of 6-inch-diameter borehole.

Demonstration Summary

The first VZCS demonstration was completed in the Immobilization Low-Activity Waste (ILAW) test area, located in the 200 East Area at Hanford (ARA 1998). This test area is free of contamination. The demonstration included testing, calibrating, and assessing the performance of the VZCS. CP push tests were conducted for the tip module (tip and sleeve stress, inclinometer, and magnetometer sensors) and the SSP (latching mechanism and multiple soil sample retrieval). Tests of the GS, XRF, and SMR modules were carried out in the laboratory and in bench-scale soil columns. Several calibration runs were conducted both in the laboratory and ex situ in the field from August to December 1998. Qualification tests were carried out from December 1998 to March 1999.

A second demonstration was carried out in the 241-S Tank Farm in the 200 West Area at Hanford between January 24 and February 9, 2000 (Bratton 2000). Eight test locations were investigated to a depth of 33–51 ft. The VZCS successfully indicated the presence or absence of radiological contamination. This information was useful to direct follow-up soil sampling with the VZCS to depths of interest at specific locations.

Key Results

The most significant results of the first demonstration are as follows:

- integration of seven miniaturized instruments into a 2-inch CP pipe,
- first use and demonstration of the Hanford 35-ton CP platform,
- implementation of a multipoint sampler design into a 2-inch CP pipe,
- design and implementation of a tip module with a magnetometer and inclinometer sensors inserted, and
- preparation and testing of MSP and SSP sensors and software to store and process data in real time.

The most significant results of the second demonstration are as follows:

- demonstration of the sampling and grouting probes,
- discovery that contamination was removed from probes during the withdrawal step, and
- discovery that compacted tank foundation soils refused penetration.

Parties Involved in the Demonstration

The following organizations partnered in developing the VZCS:

- DOE Office of Waste Management (EM-30);
- DOE Office of Science and Technology (OST, EM-50);
- Applied Research Associates (ARA), Inc., which supported modifications to the CP platform and conducted demonstration tests; and
- U.S. Army Corps of Engineers Waterways Experiment Station, which provided the MSP with XRF and GS sensors and the SSPs.

Commercial Availability and Readiness

A complete vadose zone characterization capability was developed by March 31, 1999. The VZCS was demonstrated in a radiation zone during January 2000. The system is ready for deployment in tank farms and other contaminated areas across the DOE complex.

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All published Innovative Technology Summary Reports are available on the OST Web site at http://ost.em.doe.gov under “Publications.” The Technology Management System (TMS), also available through the OST Web site, provides information about OST programs, technologies, and problems. The OST/TMS ID for the Vadose Zone Characterization System is 2118.

SECTION 2
TECHNOLOGY DESCRIPTION

Overall Process Definition

Description of the Technology

The CP is a small-diameter pipe (less than 2 inches in diameter) which is pushed by hydraulic cylinders into the ground. The CP-deployed MSP and SSP survey the soils and the subsurface for traceable contaminants of potential concern such as metals and gamma-emitting radionuclides. The CP-based system components are shown in Figure 3, and their functions are presented in Table 1. The complete system includes the following components:

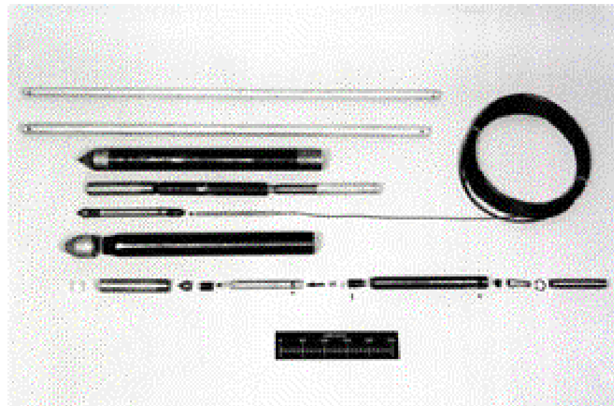

Figure 3. Components of the cone penetrometer soil sampler probe.

- push system consisting of truck- or platform-mounted CP system,
- MSP with tip modules and an umbilical cable,
- SSP with supporting hardware,
- two types of grouting tips: one for use with the SSP and a second for use with “plain” CP pipes, and
- data acquisition system (DAS) with calibration programs

Table 1. Vadose Zone Characterization System components and associated functions

Equipment and components		Function
Multisensor probe (MSP)		
Tip module	Tip stress sensor and sleeve stress sensor	• Indicate the general types and condition of soil through which the probe is penetrating
	Inclinometer sensor	• Determines cone penetrometer (CP) alignment relative to a perfect vertical path • Determines how the probe is advancing
	Magnetometer sensor	• Detects metal (or ferrous) objects in the path of the probe tip during deployment • Prevents hitting subsurface ferrous obstacles, such as buried pipes and other structures
Soil moisture and resistivity (SMR) module	Soil moisture sensor	• Determines soil moisture content for use in fate and transport analysis of contaminant migration
	Resistivity sensor	• Determines resistance of soils to applied electric currents to assist in soil type identification
Gamma spectroscopy (GS) and X-ray fluorescence (XRF) module	GS sensor	• Measures gamma-emitting isotopes
	XRF sensor	• Characterizes elemental soil contaminants • Discriminates and measures primary elements of interest when deployed at anticipated soil depths
	Umbilical cable (hard-wired to the MSP)	• Connects MSP instrumentation (i.e., GS sensor, tip module, and XRF system) to surface data acquisition system (DAS)
Multipoint soil sampler probe (SSP)		
Sample canisters, sample canister push rods, sample canister emplacement tube, tip release rod		• Withdraws multiple, discrete soil samples at the specific depths and locations identified following a prior MSP deployment and data collection
Grouting tip		

Equipment and components	Function
Grouting tip and grouting pipe unit	• Plug CP holes once the soil and plume data collection is completed
Data acquisition system (DAS) and calibration programs	
Control computer, signal processing modules, display monitors, and data storage devices	• Obtain and display data including deployment depth from the tip module and the GS and XRF sensors
Calibration procedures	• Ensure proper function and response of instrument loops within required times and parameters • Adjust settings of controllers, switches, and similar devices

Basic Principle of the Technology
The CP is moved to the push location by driving it into position onboard a truck or by crane lift from a transport trailer. Once the CP platform is in place, heavy weights are attached to achieve maximum push forces. Piping strings 3.3 ft long are pushed into the ground by hydraulic gripping tools at a rate of about 0.1 ft/second.

An enclosed tube containing the sensing and sampling probes is deployed to a subsurface position as part of the piping string. The MSP is placed in the first segment of the piping string, ensuring maximum depth of data collection. Positioning the magnetometer and inclinometer at the tip of the CP also enables a safe push by avoiding ferrous objects and preventing pipe deflection. During deployment of the MSP, the DAS, located in the CP platform, displays data on soil characterization from analytical instrumentation—the tip module, GS sensor, and XRF system.

A second CP push is made about 50 inches from the MSP push hole. The SSP is placed at the tip of a second piping string. It withdraws soil samples at selected depths identified from the data collected with the MSP during the first CP push.

Supporting Equipment
When required by established guidelines (see details in Section 6), the holes created by both the MSP and SSP pushes are grouted. Hole closure is conducted either by a separate grouting pipe or by attaching a specialized grouting head to the SSP to enable grouting upon withdrawal. If the borehole has collapsed and self-sealed, grouting may not be necessary.

System Operation

The operation of the VZCS relies on several integrated components with sensitive equipment and measurement devices that should be operated by skilled personnel. Major requirements for the proper deployment of this technology are described below.

Special Operational Parameters

Soil and subsurface conditions

- Probes can endure deployment into soils and gravels under 35- to 40-ton push or retraction forces. Under some conditions, this force will not be sufficient and the CP will not deploy the probes.

- The probes cannot be used where the soil is laden with rocks and boulders because of the potential for probe or pipe breakage. The engineered design and characteristics of the probes can reduce this constraint. For example, the probes can be fabricated from heat-treated steel to high Rockwell hardness rating.

Deployment depth

- Under the current design, probes can be deployed and can function to depths of approximately 150 ft in the vadose zone. Deeper depths at other sites may be possible. In more favorable soil containing silt or clay, depths of 300 ft have been reached.

Hole spacing

- When measuring resistance to penetration to determine soil types, operators must place holes no less than 25 times the borehole diameter from each other as prescribed by *ASTM D-3441 Standard Test Method for Deep, Quasi-Static, Cone and Friction-Cone Penetration Tests*, published by the American Society for Testing and Materials (ASTM). This standard ensures the collection of data from material that has not been disturbed by strain prior to penetration.

- According to the ASTM standard, the minimum CP hole spacing for deploying 2-inch (outside diameter) rods is 50 inches.

Sample size

- The current SSP probe configuration retrieves soil samples with a volume of 40 ml.

Maintenance and verification

- Field maintenance is needed before, during, and after CP deployment. This includes assembly and disassembly, probe calibration, and repair, as needed.

- Field verification is needed for probe operability within established performance parameters. This includes pre- and post-push quality control measurements.

Data processing

- The data collection format and driver software for the multisensor system are compatible with current industry standards and Hanford Site computing platforms. These requirements include compatibility with DOS and Windows operating systems.

- Electronic file and printout of multisensor data are generated by the system.

Grouting of CP holes

- Dry grout material such as bentonite crumbles can be used to grout holes less than 50 ft deep.

- Grouting at depths greater than 50 ft typically requires the use of low-viscosity liquid grout.

Materials, Energy, and Other Expendable Items

- Spare units are required for the CP tip and sleeve.
- Backups of all specialized equipment should be available to ensure project schedules are maintained.

Personnel Requirements
The VZCS requires specialized technical and field support personnel to operate the push platform. These personnel should be properly trained on the various systems before actual field deployment exercises. Procedures must clearly and concisely describe the equipment setup, deployment, power requirements, performance checks, data handling, and maintenance. Operator procedures and documentation must include precautions and warnings relative to proper use of all instruments and systems components, as well as safe operation of all equipment.

Secondary Waste Stream
The VZCS is considered the least disruptive tool for penetrating and characterizing the soil surrounding the tanks. An advantage of the VZCS for data gathering and sampling the vadose zone is that it generates no secondary waste such as drilling fluid and cuttings. Nevertheless, the potential for contamination of equipment has to be mitigated through the development of a plan for waste control and disposal. This plan should incorporate standard waste management practices.

Potential Operational Concerns and Risks
The following additional operational concerns must be evaluated during planning for the use of the VZCS for vadose zone characterization within a tank farm.

- A crane may be required to position the CP platform at locations with surface and subsurface obstructions common within tank farms. Use of a crane requires significant logistical planning.

- Dome loading is a concern for movement over the top of a tank.

- An operational concern is to avoid damage to underground tanks, piping, utilities, and instrument lines within tank farms.

- Procedures must be in place to control potential underground contamination.

SECTION 3
PERFORMANCE

Demonstration Plan

Demonstration Description

A demonstration of the VZCS was conducted from August to December 1998 at the ILAW test area located inside the 200 East Area at Hanford. This demonstration tested the instrument configuration, tested the operations of the platform, and provided personnel training. The ILAW test area is an easily accessible, uncontaminated site that has been used for several other demonstrations.

A second demonstration of the VZCS was conducted between January 24 and February 9, 2000, at the S-Tank Farm located in the 200 West Area at the Hanford Site. This demonstration was performed to determine the ability to locate subsurface contamination and to evaluate sampling and grouting probes. Pushes were made over the known plume southeast of Tank S-104 and in other locations of suspected plumes between tanks S-101, S-102, S-104 and S-105.

Major Objectives

The primary objectives of the demonstration in the ILAW test area were as follows:

- Employ reusable MSP and SSP sensor systems.
- Obtain soil samples and in situ data for comparison between field and lab analytical results.
- Demonstrate the capability to obtain multiple soil samples during a single push.
- Test the ability to detect and avoid subsurface metal objects during probe deployment.
- Demonstrate the aptitude of the grouting modules to seal holes during or after extraction of the VZCS.
- Calibrate and test the data acquisition and processing systems.

Based on the results of the demonstration, the following capabilities for the VZCS are expected in an actual deployment:

- Gather information at sufficient depth to evaluate vadose zone conditions.
- Characterize the aerial extent of contamination adjacent to underground storage tanks.
- Survey for target contaminants to achieve more efficient follow-up sampling and monitoring strategies.

Major Elements of the Demonstration

Developmental testing was conducted both in the laboratory and at the ILAW test area at the Hanford Site. Testing included all aspects of the VZCS and probes, instrument calibration and verification, and data acquisition and processing systems. Table 2 presents the functions tested for each system component.

Table 2. Capabilities of VZCS components

System Component	Capability
Cone penetrometer	• Add or remove pipe strings from the entire pipe string as needed
Multisensor probe (MSP)	• Concurrent and independent operation of the XRF sensor and DAS, the GS detector system, and tip module sensors • Operate continuously for a minimum of 10 h • Provide in situ measurements of independent, discrete samples and measurements during penetrometer push activity • Operate over a temperature compensation range of 40–120ºF

System Component	Capability
MSP tip module (tip sensors include tip and sleeve stress, magnetometer, and inclinometer sensors)	• Magnetometer detects ferrous objects at a minimum distance of 2 inches in front of the moving probe • CP push reacts correctly, i.e., stops, slows down, or withdraws slightly, in sufficient time to avoid hitting detected objects
MSP umbilical cable	• Flexible enough to deploy within multiple CP piping elements • Length of 330 ft accommodates handling, storage requirements, and computer hookup at depths up to 150 ft • Surface is free of friction, abrasion, and wear inside the CP pipe • Withstands the physical stresses of deployment and does not allow degrading or damaging wire integrity and performance
Soil moisture and resistivity module: soil moisture sensor and resistivity sensor	• Determines soil moisture content with a minimum reporting limit less than 5% • Determines resistance of soils to applied electric currents to assist in soil type identification
Gamma spectroscopy (GS) sensor	• Records gross gamma counts at rates 10–10,000 counts per second • Detects gamma signals in the energy range 100–3,000 keV • Detects ^{137}Cs contamination at a minimum detection limit of 10 picocuries per gram (pCi/g) • Capable of a range of view of approximately 12–18 inches around the detector • Detects ^{137}Cs, ^{60}Co, and Th
X-ray fluorescence (XRF) sensor	• Interrogates soils adjacent to single, X-ray–transparent window in module housing • Detects fluorescent X-ray lines with energies exceeding 8 keV that are emitted by elemental components whose concentrations exceed 100 parts per million (ppm) by weight • Detects Sr, Zr, Tc, Pb, and U • Detects U at a minimum detection limit of 100 ppm by weight • Instrument repeatability should have relative standard deviation of less than 1% for 10 repeated measurements of count time not exceeding 300 seconds real time
Soil sampler probe (SSP)	• Retrieves five soil samples during a single CP push event • Retrieves samples containing approximately 40 mL • Rugged sampling canister and assembly withstand rigors of sampling • Light enough to be withdrawn and managed by hand by operators on the surface, even when the full length of CP pipe (about 150 ft) is deployed • Minimal internal CP piping contamination, sample cross-contamination, and mixing of samples when multiple samples are taken

System Component	Capability
Data acquisition system (DAS)	• Uses multifunctional processors, display devices, and multiple window control systems to minimize space required in the control trailer • Stores raw sensor data electronically for reference, data reduction, and post-acquisition operations with reference to date and time of data element acquisition • Applies real-time corrections/adjustments to MSP raw data files • Applies corrections for GS temperature compensation, XRF source decay, and other corrections required to assure and control the quality of the MSP sensor data • Enables real-time or on-demand viewing of raw data, corrected spectra, and processed data from the MSP sensors • Enables on-demand viewing of depth profile trend charts of operator-selected sensor on the DAS system monitor • Plots and displays up to four trend charts (for differing combinations of probe sensor data inputs) on the system monitor • Supports production of hard-copy reports
Calibration system	• Reflects measurements related to the target environment of use • Calibrates all system components and verifies performance against specifications
Grouting capability	• Conducts separate, follow-up push into the hole made by the MSP with a dedicated pipe string to desired depth

Results

The demonstration at the ILAW Test Site produced the following major results:

- Seven miniaturized instruments were successfully integrated into the 2-inch-diameter CP pipe.
- Sensors and probes were demonstrated at the ILAW Test Site and tested in the laboratory.
- Multiple soil samples were obtained during a single CP push.
- Metal objects were detected using the magnetometer sensor within specified ranges.
- GS and XRF functions tested properly over specified operating ranges.

Some of the tests were conducted in the laboratory, and calibration runs were conducted both in the laboratory and ex situ in the field. CP push tests were conducted in the field for the tip module (tip and sleeve stress, inclinometer, and magnetometer sensors) and the SSP (latching mechanism and multiple soil sample retrieval). Tests of the GS, XRF, and SMR modules were carried out in the laboratory and in bench-scale soil columns. A detailed account of testing results is provided in the developmental test report (ARA 1998). Table 3 summarizes the results.

Table 3. Results of Performance Tests

Equipment	Component	Test Results
Multisensor probe (MSP)—tip module	Tip stress sensor	• Verified within allowable 2% of measured reference load
	Sleeve stress sensor	• Verified within allowable 2% of measured reference load
	Soil stratigraphy derived from tip and sleeve sensor	• Completed using standard procedures • Soil stratigraphy profiles produced
	Inclinometer sensor	• X- and Y-axis inclinations verified within allowable 2% error • Field test inclination profiles produced
	Magnetometer sensor	• Detected within allowable error of 1/8 inch or up to 2%
Soil moisture and resistivity (SMR) module	Soil moisture sensor	• Soil moisture content calibrated with a minimum reading of 3.2% (<5%, as required)
	Resistivity sensor	• Verified at four resistance values (0 to infinity)
Gamma spectroscopy (GS) and X-ray fluorescence (XRF) module	GS sensor	• Tested within operational ranges and for target contaminants • Obtained a resolution of 7.5%, 1% lower than specification • Tested minimum detection limit for ^{137}Cs at 2.5 pCi/g versus specified 10 pCi/g
	XRF sensor	• Tested within operational ranges for most specifications • Further testing is recommended for upper temperature range • Detector resolution specification of less than 5% was met
	Umbilical cable (hard-wired to the MSP)	• No issues reported
Multipoint soil sampler probe	Sample canisters, sample canister push rods, sample canister emplacement tube, tip release rod	• Operated smoothly with no problems • Latching mechanism worked properly • Collected multiple samples, but sample chamber did not fill completely every time; additional checking is required
Grouting tips	Grouting tip and grouting pipe unit	• No results or issues reported
Data acquisition system (DAS) and calibration	Control computer, signal processing modules, display monitors, and data storage devices	• Software, hardware, and data communications tested and verified
	Calibration procedures	• Tested and verified

SECTION 4
TECHNOLOGY APPLICABILITY AND ALTERNATIVES

Technology Applicability

The VZCS is applicable at sites where geologic conditions permit penetration of the CP piping to the desired depth. The optimum application of CP technology is at sites where the subsurface can be penetrated using forces up to 40 tons. Sites that typically can be characterized using a CP contain surficial unconsolidated sediments, except those characterized as difficult to drill because of large boulders or cemented layers.

In favorable soil conditions where the CP has a rapid penetration rate, the VZCS could sample between boreholes to verify the presence of contaminants. Another use of this technology would be to commence the push at the bottom of existing boreholes to obtain information on the lower vadose zone. This method may be more economical than attempting to extend an existing borehole with a smaller-diameter cable tool.

Additional features of the VZCS include the following:

- It can effectively penetrate as deep as 300 ft but is generally limited to depths up to 150 ft.
- Greater depths can be reached when used in conjunction with drilling methods.
- It is best if applied to exploratory purposes that provide initial site characterization data, which are confirmed by collecting samples for analysis in the laboratory.
- It enables more judicious selection of monitoring well locations. More representative samples can be collected at relatively lower costs.
- It emplaces monitoring devices in the subsurface, enabling subsequent gamma/neutron logging.

Competing Technologies

The VZCS is an innovative technique for subsurface characterization. Conventional techniques generally require the emplacement of a borehole using drilling, driving, or pushing techniques. Dry-well gamma logging is then used for measurements.

The baseline technology is subsurface drilling, soil sampling during drilling, and gamma measurement inside the borehole casings. Boreholes at the Hanford Site are typically drilled with a cable tool drill, which uses the periodic dropping of a weight to drive a core barrel and subsequently a steel liner into the ground. As the well is drilled, samples are taken with a device known as a split spoon, which captures material from the bottom of the hole as the hole is drilled. Samples are then analyzed in the laboratory. Spectral gamma logging measurements are taken inside the casing when the well is completed.

The VZCS has several advantages when compared to the baseline. The footprint of the VZCS is smaller than a conventional drill rig; therefore, it can be located in confined spaces within tank farms. The VZCS contains sensors to help detect and avoid metal subsurface objects. The VZCS disturbs only a 2-inch-diameter core of soil, compared to 6 inches or more for conventional drilling. The VZCS generates no waste, compared to the contaminated drilling mud, which must be contained in expensive packaging for burial in a disposal site for low-level or mixed waste.

The baseline method uses dry-well gamma logging, which cannot detect the presence of radionuclides other than gamma emitters because of the metal borehole casing. The sensors in the cone penetrometer come in contact with soil directly to enable a broader range of analytic capability.

The baseline has the inherent disadvantage that the distribution and nature of the constituents of concern may not be well known prior to drilling the well or during the drilling of the well. By contrast, the VZCS can survey for contaminants of concern as the CP is pushed through the soil.

Other direct-push alternative characterization and sampling technologies include the following:

- The Geoprobe, a lightweight, direct-push sampling device with the following characteristics:

  - The maximum depth of application at the Hanford Site is 33 ft.
  - Soil conductivity data, soil, and shallow groundwater samples can be collected.
  - Angled-push capability is available.
  - A continuous soil core is obtained, resulting in more waste produced.

- The Enviro-Core, a lightweight, direct-push sampling device with the following features:

  - Combines percussion, hydraulic, and vibratory push technologies.
  - The maximum depth in ideal geologic conditions is 50 ft.
  - Soil vapor data collection, shallow groundwater sampling, and piezo-well installation are possible.
  - Self-grouting is available.
  - Angled-push capability is available.
  - A continuous soil core is obtained, resulting in more waste produced.

Patents/Commercialization/Sponsor

Several DOE sites have sponsored demonstrations and tests of various versions of CP-deployed sensors. OST has supported a number of demonstration projects under the Tanks Focus Area; the Subsurface Contaminants Focus Area; and the Characterization, Monitoring, and Sensor Technology Crosscutting Program.

ARA, Inc. provided rework of the soil sampling probe to improve reliability over the initial version delivered by the U.S. Army Corp of Engineers Waterways Experiment Station. ARA improved the MSP by adding the soil moisture sensor, improving the GS crystal and electronics and reengineering the XRF sensor. ARA also modified the CP platform to accept the VZCS for use at the Hanford Site. Currently, ARA operates two research CP rigs under contract to DOE. ARA is incorporating a wide variety of sensors into the CP.

Numerous developments in CP technologies are now commercially available. At least ten companies provide basic services. Refinements in the technology are quickly being developed, and the technology is being deployed at numerous sites.

SECTION 5
COST

Methodology

The VZCS uses the CP instead of cable tool drilling to access the vadose zone. The purpose of this section is to estimate the cost savings associated with the use of the VZCS. The costs relative to VZCS technology deployment are compared to those of the baseline technology, cable tool drilling.

Cost Analysis

Baseline Technology: Sampling and Logging Wells (Cable Tool Drilling)

- Wells are drilled to 150–250 ft.
- Actual locations within tank farms for cable tool drilling rigs are extremely limited by surface and subsurface equipment and utilities. Typically, there is little access directly over plumes of contamination under or near the tanks.
- The drilling rate is 8 ft/day, requiring 20 to 30 days to drill a well.
- The completed wells have steel casing for the entire depth.
- The cost of a borehole in a tank farm is typically about $1.2 million.
- Tank farm operational and program costs are approximately double the cost of the drilling contract.
- For example, a $1.2 million borehole would typically include a $400,000 drilling cost and a $800,000 tank farm operational support and program cost.
- Soil samples from borehole drilling are sent to analytical laboratories; results are available in months.

Vadose Zone Characterization System Cone Penetrometer Technology

- CP pushes are as deep as required or until refusal by hard formations.
- A 50-ft push can be completed in 4 hours.
- No waste is generated.
- Grouting of 2-inch penetrations requires smaller amounts of grout.
- Analysis of gamma-emitting contamination is performed in real time.
- The first push will determine the depths of contamination.
- The second push will grout the first survey hole.
- The third push will obtain samples at the desired depths.
- The fourth push will grout the sample hole.
- Eight pushes were performed in a radiation zone for $76,000.
- Gamma radiation was profiled to as deep as 45 ft.

The total cost to perform eight CP pushes totaling 371 ft was $323,000. This project cost had three components:

ARA contract	$ 76,000
Estimated tank farm operational support costs	100,000
Program costs	147,000
	$323,000

ARA supplied VZCS and the staff to operate the equipment. ARA performed gamma logging during the CP pushes, grouted the CP holes, and took soil samples. ARA provided an engineer and two CP operators.

Tank farm staff provided radiation and contamination control. Tank farm staff packaged the soil samples and delivered samples to the analytical laboratories. As a rule of thumb, the cost of the tank farm support staff and program costs is generally estimated to be double the cost of the off-site drilling contractor.

Program costs include planning, program support, contract costs, engineering support, and overhead. These costs remain the same regardless of the depth of push and number of locations analyzed by the VZCS.

Cost Benefits
Cost benefits of the VZCS include the following:

- Costs for subsurface characterization are less than for cable tool drilling methods if applied for survey purposes to provide initial site characterization data.
- More representative samples can be collected at relatively lower costs.
- More judicious selection of borehole locations is possible; fewer boreholes may be required.

Cost Conclusions

Using the VZCS to supplement conventional borehole drilling has the potential to obtain greater amounts of characterization data for significantly less cost. A total of 371 ft of soil was characterized in the S Tank Farm for $323,000, in contrast to approximately $1.2 million for a typical 150-ft borehole. The VZCS can characterize a foot of soil for about one-tenth the cost of cable tool drilling.

Additional cost savings accrue from the use of the VZCS to optimize the location for future boreholes. The cost of a $1 million borehole located in a nonproductive location will now be avoided.

Further cost savings can be attributed to obtaining real-time analytical information.

SECTION 6
REGULATORY AND POLICY ISSUES

Regulatory Considerations

Hanford regulatory requirements were analyzed for potential tank farm deployments. Hanford Site SST farms are in waste management areas regulated by the State of Washington Department of Ecology (Ecology). Washington Administrative Code (WAC) 173-160 specifies the regulatory, permitting, and safety issues related to well drilling, completion, and abandonment activities undertaken at the tank farms at Hanford.

Regulations for borehole closure are ambiguous for the Hanford Site. According to WAC 173-160-010(3)(g), CP borings are considered uncased geotechnical borings. Under these conditions, the sampling locations could be abandoned pursuant to Chapter 90.48 of the Revised Code of Washington (RCW) and WAC 173-160-010(4) in such a manner as to "ensure protection of the groundwater resource and prevent contamination of that resource." This provision means that an abandoned hole should be grouted in all situations where groundwater quality may be compromised.

Ecology adopted a modified position pertaining to well and boring abandonment in a letter dated February 22, 1993, from C. Cline (Ecology) to S. Wisness (DOE). It was declared that the requirement relevant to grouting of Hanford borings is WAC 173-160-420, which states that "Uncased wells shall be backfilled with concrete, grout, puddled clay, or high-solids bentonite." In other words, Ecology has taken a position that all borings at Hanford are wells that must be grouted. However, a variance to WAC 173-160-420 was provided for boreholes left without grouting. It required the collection of data before and during deployment, which can be used to make a technically defensible decision on the need to grout the borehole. Therefore, the decision to place a surface seal, seal selected intervals, or grout the entire boring and the selection of grout type to be used must be done according to Ecology regulations and rules.

Secondary Wastes

Secondary wastes from the deployment of the VZCS primarily remain in the borehole after the CP is removed from the ground.

CERCLA Evaluation

This section summarizes how the VZCS addresses the nine Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA) evaluation criteria.

1. *Overall protection of human health and the environment*

   - Inspecting and monitoring tank farms with hazardous or radioactive components significantly minimizes exposure to future generations.

2. *Compliance with applicable or relevant and appropriate requirements (ARARs)*

   - The VZCS meets applicable regulatory requirements.
   - Established procedures and controls are in place to ensure compliance.

3. *Long-term effectiveness and permanence*

   - This technology can help reduce long-term risk from tank farm leaks.

4. *Reduction of toxicity, mobility, or volume through treatment*

   - This system reduces the number of unproductive boreholes, thereby reducing potential vertical pathways for surface water transport to the vadose zone.

- This system helps to identify potential vadose zone contamination for monitoring and cleanup.

5. *Short-term effectiveness*

   - Radiation exposure to workers is maintained as low as reasonably achievable (ALARA).
   - Data collection is done remotely.
   - Established procedures and controls exist, and workers are thoroughly trained and qualified.

6. *Implementability*

   - The VZCS was successful in cold (nonradioactive) tests.
   - Worker training and qualification programs and procedures are in place.

7. *Cost*

   - Cost data and cost savings analysis is provided in Section 5.

8. *State (support agency) acceptance*

   - The State of Washington and the Hanford Site have agreements that cover regulatory issues and establish requirements for deployment of the VZCS and subsequent borehole abandonment.

9. *Community acceptance is discussed below.*

   - Tanks can be isolated faster, with fewer personnel, and in much safer surroundings, thus reducing threats to human health and the environment.

Safety, Risks, Benefits, and Community Reaction

Deployment of the VZCS has positive community reaction because it leads to improved knowledge of potential subsurface contamination from past leaks from underground storage tanks in the tank farm areas. This would ultimately mitigate the risk of further groundwater contamination. However, there are safety concerns associated with any penetration of tank farm soils.

Risk is also reduced due to a large decrease of drilling waste that may contain radioactive and hazardous contaminants requiring special handling and disposal. Additionally, the use of a VZCS for surveying sampling locations results in a reduction of analytical testing requirements. In all cases, worker safety is improved and risks are reduced. However, there is a risk that vadose zone contamination could move if surface water entered abandoned CP holes. This risk is mitigated by sealing abandoned holes at the surface and, where necessary, grouting the entire depth of the hole.

Additional benefits include faster deployment for a quicker determination of the nature and extent of contamination. The time needed to survey and sample the vadose zone for contaminants of concern in the 200 Area tank farms at Hanford can be significantly reduced. The real-time nature of data acquisition and processing, combined with a flexible site investigation program, can be used for rapid decision making and deployment, which can significantly improve the quality and optimize the duration and cost of investigations.

SECTION 7
LESSONS LEARNED

Design Issues

The following issues must be addressed in the design and engineering of the VZCS:

- The probes must be engineered to function under the geologic conditions anticipated during their deployment within the operating tank farm environment.
- A pedigree of historical data must be established to be used for calibration purposes and for completeness of data records.
- The design of the SSP must minimize the opportunity for internal CP piping cross-contamination and mixing of samples when multiple samples are taken.
- The SSP design should accommodate a grouting tip that could be placed in the SSP upon completion of the sampling effort to close the borehole with grout on withdrawal.
- Bending of the overall pipe string during deployment must be prevented under normal conditions.
- The minimum detection levels of the GS and XRF sensors for specific target analytes at the site of deployment should be measured in a prepared test matrix. Measured performance in a test matrix should meet the minimum requirements.

Implementation Considerations

Failure to plan for operational considerations can impact a successful data collection program. For example, aerial, surface, and subsurface obstructions may constrain positioning probes at the desired sampling location. The CP platform must be moved to the push site by trailer truck, then positioned using a crane. Combined weight and space restrictions must be considered in deployment planning so that enough information is gathered to adequately characterize the site. Prior to deployment to in tank farms, the target site should be studied to identify physical constraints.

To reach maximum penetration depths, it may be necessary to “cycle” the CP piping string by occasionally moving the pipe up several inches to release accumulated tip- and side-load soil pressures and then proceeding down again.

An important decision is whether to grout the hole. Options include placing a surface seal, sealing selected horizons, or grouting the entire boring. During deployment tests, subsurface data should be collected and analyzed to guide grouting decisions. Selection of the grout type and the method of closing a CP hole are based on site-specific hydrogeologic and contaminant conditions as well as state and federal rules and regulations.

Table 4 lists factors that influence grouting decisions. A variance requiring only limited subsurface grouting may be applicable to the following situations:

- Contamination is restricted to only a few stratigraphic horizons.
- Only immobile contamination is found.
- Perched water is absent, and moisture content is low.
- A boring is predominantly in geologic facies subject to rapid collapse after rod extraction.

Table 4. Factors that influence grouting decisions

Factor	Is grouting required?
Regulations 90.48 RCW and WAC 173-160	Grouting is required in lieu of a variance. Factors to be addressed in a request for variance are listed below.
Site geology	• No, if perched water not present or laterally discontinuous or if there is a low soil moisture flux. • Yes, if perched water widespread and/or contains contamination or if there is a high soil moisture flux.
Perched water/soil moisture	• No, if boring predominantly in collapsible sand and gravel. • Yes, if cohesive silt constitutes >25% of strata penetrated by boring, except if layers laterally discontinuous.
Multiple penetrations at a single setup	• No, if no to all of above. • Yes, if yes to any of above.
Subsurface contamination	• No, if immobile. • Yes, if mobile.

Technology Limitations and Needs for Future Development

Additional development should be conducted to increase achievable depths and broaden the geologic conditions for which the VZCS can be used. The technologies are currently limited to sites where geologic conditions permit penetration of the CP with platforms employing forces of up to about 40 tons. Candidate sites typically contain surficial unconsolidated sediments that do not include large boulders or cemented layers.

If possible, grouting of borings should be avoided, and grouting of closely spaced borings should be postponed until all data collection objectives are achieved. Widespread accumulations of grout in tightly spaced borings may impact future sampling for waste storage and retrieval needs yet to be determined. Assessment of such methodologies and approaches may need to be investigated to achieve regulatory acceptance.

A major source of data is from soil samples that are analyzed ex situ. Additional sensor technology can increase the amount of information that can be collected in situ and in real time.

Technology Selection Considerations

There are several reasons for selecting the VZCS:

- No other soil screening and interrogation methods are currently available for rapid deployment.
- Other methods and tools would require two to five years to develop and demonstrate.
- Where it can be used, the VZCS technology offers a fast, efficient method to evaluate unsaturated soils to targets depths to 150 ft.

Issues that need to be addressed to assess the capability of the technology include the following:

- depth of contamination and soil conditions,
- testing at contaminated sites to validate field performance of various probes and apparatus, and
- safety concerns and weight constraints when operating the CP platform and crane in the tank farm with aboveground and underground obstructions.

APPENDIX A
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APPENDIX B
ACRONYMS AND ABBREVIATIONS

ALARA	as low as reasonably achievable
ARA	Applied Research Associates, Inc.
ARAR	applicable or relevant and appropriate requirements
ASTM	American Society for Testing and Materials
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act of 1980
Ci	curie
Co	cobalt
CP	cone penetrometer
Cs	cesium
DAS	data acquisition system
DOE	U.S. Department of Energy
Ecology	Department of Ecology of the State of Washington
GAO	Government Accounting Office
GS	gamma spectroscopy
ILAW	Immobilization Low-Activity Waste
MSP	multisensor probe
OST	Office of Science and Technology
Pb	lead
PNNL	Pacific Northwest National Laboratory
RCW	Revised Code of Washington
SMR	soil moisture and resistivity
Sr	strontium
SSP	soil sampler probe
SST	single-shell tank
Tc	technetium
Th	thorium
TMS	Technology Management System
U	uranium
VZCS	Vadose Zone Characterization System
WAC	Washington Administrative Code
XRF	X-ray fluorescence
Zr	zirconium